Engineering Properties and Maintenance of Golf Putting Greens

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Phase One: Engineering Properties

Introduction.

The primary objective of the first portion of the project has been to apply the principles of geotechnical engineering to the question of ensuring stability of sand-textured rootzones used in golf putting greens in the context of present agronomic knowledge. We have chosen to initiate our study with a complete investigation of the literature and have followed that with the characterization of sands falling within present-day specifications. Our next step was to measure strength and deformability parameters of the selected sands with the continued work of relating soil strength to soil physical properties. We have also spent a great deal of time and effort in the development of a field-test for the measurement of soil strength and bearing capacity on many different putting greens (sand, push-up, topdressed, old, new, etc.) with different turfgrass species at different times of the year.

We are pleased with our initial progress and hope to be even more productive in the coming months.

Literature review

Effect of Grain Size

The shear strength of sands was first introduced by Coulomb. He simply assumed that frictional resistance increases with normal pressure. In fact, there are three components contributing to the strength of sand. According to Rowe (1962), these components are:

1. strength mobilized by frictional resistance;
2. strength developed by energy required to cause expansion or dilation of materials; and

3. strength developed by energy required to rearrange and reorient materials.

The first component is usually described as sliding friction, the second as interlocking friction, and the third as rolling friction.

Yong (1975) explained that sliding friction is included by microscopic interlocking arising from surface roughness; interlocking friction is caused by the physical resistance to relative particle translation affected by adjacent particles. The third component, rolling friction, might be ignored.

Koerner (1970a) investigated the influence of the effective size D_{10} for saturated sandy soils. The effective size was varied from fine gravel (2.6mm) through clay sizes. The results showed that friction angle increases with decreasing particle size. Zelasko et al. (1075) tested three sands and found that an increase in mean particle diameter causes a slight decrease in friction angle. Furthermore, it was indicated that the effect of particle diameter appeared insignificant. Bishop (1948) also made the same conclusion . Kirkpatrick (1965) studied the effects of particle size from tests on two cohesionless materials. Results showed that an increase in grain size reduces the friction angle. Hough (1957) explained that particle size affects the development of strength by influencing the amount of shearing displacement required to eliminate interlocking and to bring the solids to a free-sliding position.

In summary, the effect of particle size on friction angles of cohesionless materials is not clear through the literature. The main reason for the conflict may be the difficulty in separating all the contributing variables (such as texture and mineralogy) that influence the relationship between friction angle and particle size.

Effect of Grain Size Distribution

In general, the results of sieve analysis for cohesionless soils are presented as grain-size distribution curves. The diameter in the grain-size distribution curve corresponding to 10 % finer is defined as the effective size D_{10}; 60 % finer is D_{60}. Then, the uniformity coefficient C_u is given as $C_u = D_{60}/D_{10}$. A higher value of C_u indicates the soil sample is well-graded.

Bishop (1948) tested a full range of cohesionless soils (from sands to sandy gravels) in shear box tests. Two samples were of particular interest, a well graded sand of the Folkeston bed (C_u=2.5) and Ham River sand which is a uniform sieved fraction from the Thames Valley gravels (C_u=1.3). It was observed that in the plot of porosity versus friction angle, the curves of the two samples were almost parallel. Due to the lack of limiting porosities, the effect of C_u is not clear. Chen (1948) studied the strength characteristics of cohesionless soils by using triaxial compressions tests. He concluded the friction angle of these soils increases with increasing uniformity coefficient, varying from 25.5° for loose specimens to 51.5° for the well graded gravel.

Koerner (1970a) studied the effect of gradation on the strength of cohesionless soils using three single mineral particles (quartz, feldspar, and calcite). Gradation was evaluated by varying uniformity coefficient (Cu) from 1.25 to 5. The quartz soils were tested in the saturated and air-dry conditions with both drained and undrained triaxial tests. The conclusions were:

1. The drained friction angle for saturated feldspar and calcite soils increase with increasing value of C_u;

2. The effect of Cu on the drained friction angle for both saturated and dry quartz soils is negligible; and

3. C_u does not affect the undrained friction angle of quartz soils.

Zelasko et al. (1975) performed triaxial compressions tests using sand materials mainly consisting of quartz grains and the range of C_u values ranged between 1.2 and 2.0. Similar conclusions to Koerner's study were found that improved gradations have a minor influence on friction angle.

Effect of Grain Shape

In general, grain shapes of cohesionless soils were determined by examination of photomicrographs. There are two widely accepted definitions of grain shape which are roundness and sphericity. The concept of roundness was first proposed by Wadell (1935). The definition of roundness is defined as the ratio of the average of the radii of the corners of a sand grain image to the radius of the maximum circle that can be inscribed within the grain image. The range of roundness value is between zero and one. Furthermore, Youd (1973) added descriptions for roundness values which are given in the reference.

Zelaslo et al. (1975) concluded that friction angles decrease significantly with increasing particle roundness based on the experimental study of three sands. Increased roundness causes decreased frictional resistance between particles. However, there was an exception that strengths of three smaller sizes of one of the sands were lower that that of the larger particle size of that sand.

Koerner (1970a) studied the effect of particle shape as measured by its sphericity and angularity using three different saturated samples. The results showed the less spherical and more angular soils had significantly higher friction angles.

From the literature it is relatively clear that friction angle increases with increasing angularity.

Gradations of sand

Sand is the primary component of the USGA root zone mix. Turfgrass growth and stability is greatly influence by sand grain size, uniformity, and shape. The 1973 USGA Specifications (USGA Green Section Staff.1973) was the first set of published standards that established an acceptable grain size distribution for the root zone mix. These specifications designated that the mix should contain no particles greater than 2mm, not more than 10% greater than 1mm, and not more than 25% less than .25mm, including a maximum 3% clay and 5 % silt. The current specifications, 1993 USGA Specifications (USGA Green Section Record.1993), allows for coarser particles, an increase in medium range particles, and an decrease in very fine grain size particles. Table 1 lists the current specifications of the root zone mix.

Table 1. Current United States Golf Association particle-size distribution specifications.

PARTICLE SIZE DISTRIBUTION OF USGA ROOT ZONE MIX			
Name	Particle Diameter	Specification	
Fine Gravel	2.0-3.4 mm	Not more than 10% of the total particles in including a maximum of 3% fine gravel (preferably none)	
Very coarse sand	1.0-2.0 mm		
Coarse sand	0.5-1.0 mm	At least 60% of the particles must fall in this range	
Medium sand	0.25-0.50 mm		
Fine sand	0.15-0.25 mm	Not more than 20% of the particles may fall within this range	
Very fine sand	0.05-0.15 mm	Not more than 5% in this	Total particles
Silt	0.002-0.05 mm	Not more than 5% not	range should
Clay	> 0.002 mm	Not more than 3%	exceed 10%

Particle distribution influences many important parameters of the root zone mix. Kunze (1956), Howard (1959), and Baker (1983) all have concluded that the .25 to .5 mm range exhibits the best physical properties for putting green root zones. Particle uniformity and shape influences the interpacking of sands. Two important parameters define particle uniformity. Coefficient of uniformity (C_u) is defined as: $C_u = D_{60}/D_{10}$. The other parameter, coefficient of curvature is defined as: $C_c = (D_{30})^2/(D_{10})(D_{60})$. D_{10}, D_{30}, and D_{60} are defined as the following:

> D_{10} = grain diameter (in mm) corresponding to 10% passing by weight(or mass)
> D_{30} = grain diameter (in mm) corresponding to 30% passing by weight(or mass)
> D_{60} = grain diameter (in mm) corresponding to 60% passing by weight(or mass)

A sand with a C_c value between 1 and 3 along with a C_u value greater that 6 is considered to be well-graded. The coarsest and finest USGA gradations demonstrate uniformity by the following values: C_c=1.36, C_u=1.02 (coarsest gradation) and C_c=2.13, C_u=1.30 (finest gradation).

Strength of Sands

Friction Angle

The Mohr-Coulomb strength equation relates shear stress(τ) to normal stress(σ) at failure to obtain strength parameters ϕ (friction angle) and c (cohesion). The following is the Mohr-Coulomb strength equation:

$$\tau_{ff} = \sigma_{ff} \tan\phi + c$$

Since sand is cohesionless, c is considered to equal zero for the mohr-columb equation. The coefficient of friction can be determined by a direct shear test (ASTM D 5321). A Direct Shear machine was used to obtain normal and shear stresses at failure under various normal loads. A failure envelope is established by relating shear stress to normal stress at failure, which in turn establishes the friction angle (ϕ). The friction angle can be related to density or void ratio to establish a relationship between strength and particle interpacking. Direct shear test were run on 2NS, soil mix, crushed stone, and various processed forms of 2NS, soil mix, and crushed stone within USGA specifications. Test conditions included the following: dry compacted, dry uncompacted, wet compacted, wet uncompacted.

CBR(California Bearing Ratio) Test

The California Bearing Ratio test is an empirical test developed in the 1930's for determining a bearing capacity value of highway sub-bases and subgrades. CBR is defined as the ratio of the force required to penetrate a circular piston of 1935

mm^2 ($3in^2$) cross-section into soil in a special container at a rate of 1mm/min (0.05 in/min), to that required for similar penetration into a standard sample of crushed rock. (Head, 1994). The ratio is determined at penetrations of 2.5 and 5.0mm (0.1 and 0.2 in^2). The equipment used for both the field and lab CBR test can be slightly modified, along with the test procedures, to develop a measurement of turfgrass stability under applied vertical loads.

Lab CBR Equipment/Triaxial Equipment

The stability of experimental sands can be tested by using an Triaxial Loading Frame with a 2 in. dia. CBR penetration piston attached to vertical load cell. A CBR mold (6 in. inner dia, 7 in. high) is placed on a circular base plate which is load vertically upward at variable speeds (.00007 to .2 in/min). By attaching a vertical dial gauge to the CBR mold, the resultant normal load can be recorded against the vertical displacement until failure of the sand is observed. The sand can be tested dry-uncompacted, dry-compacted, moist-uncompacted, and moist-compacted to determine the optimum stability conditions of representative sands. The results obtain from this test includes bearing capacity vs. deformation.

Field CBR Equipment

The stability of the turfgrass structure can by determined by the use of the Field CBR device. The Field CBR device consists of a 2 in.diameter penetration piston attached to proving ring (force gauge), which is attached to a mechanical screw jack. This system is clamped to a truck bumper or any similar machine that will provide a suitable reaction. A vertical dial gauge is mounted to the penetration piston and positioned on a horizontal steel beam to record force vs. displacement as the piston is loaded vertically downward. The penetration piston is load vertically into 4, 6, and 8 diameter circular plates which represent an area similar to that of tires and athletic shoes. Again, force vs. displacement is recorded until failure of the turfgrass structure is observed. This test may be conducted with or without the layer of turfgrass to determine the strength of the underlying sand structure. The results obtain from this test includes bearing capacity vs. deformation.

Direct Shear Test/Coefficient of Friction

The direct shear test is a relatively simple way of determining the strength parameters of a soil (c and ϕ). ϕ refers to the coefficient of friction(or angle of internal friction) and c refers to the cohesion of the material. The Mohr-Coulomb strength equation ($\tau_{ff}=\sigma_{ff}\tan\phi + c$) for a soil specimen can be solved through the direct shear test. If sand, a cohesionless material, is the material to be tested, the c variable in the above equation drops out, becoming $\tau_{ff}=\sigma_{ff}\tan\phi$.

The direct shear apparatus consists of a 3 15/16in. X 3 15/16in. brass box which is divided into two equal halves. The test specimen is sheared with the top half of the shear box remaining stationary as the bottom half is sheared at a controlled rate of displacement. A force measuring device (a proving ring or load cell) is positioned in direct line with the stationary half of the shear box. The test is administered by applying a normal force upon the shear box and shearing the box to the right or left. Horizontal displacement is recorded vs. shear force and vertical displacement until failure of the specimen is achieved. The coefficient of friction can be determined by plotting shear stress vs. normal stress at failure of representative normal loads. The sand can be tested dry-uncompacted, dry-compacted, moist-uncompacted, and moist-compacted to determine the optimum stability conditions of representative sands.

Coefficient of Friction

The coefficient of friction can vary according to the condition of the sand being tested. The minimum value for ϕ is called the angle of repose. This angle is the steepest stable slope for loosely packed sand. Peak friction angles in a dense, well-graded, coarse sand usually range from 37° to 60°; for a dense, uniform, fine sand they are usually between 33° and 45°. (Lambe,1951).

Bearing Capacity/Friction Angle

Ultimate bearing capacity and friction angle values from the direct shear, lab CBR, and field CBR tests can all be tied together and a conclusion drawn relating strength and stability of the experimental sands to their gradation, particle size, and particle shape by applying the results to an empirical bearing capacity model. This is done by applying bearing capacity values of different size plates to the bearing capacity equation and then back-calculating the value of the friction angle. According to Meyerhof (1963) the ultimate bearing capacity equation is defined as the following:

$$q_u = cN_cF_{cs}F_{cd}F_{ci} + qN_qF_{qs}F_{qd}F_{qi} + 1/2\gamma BN_\gamma F_{\gamma s}F_{\gamma d}F_{\gamma i}$$

where

- c=cohesion
- q=effective stress at the level of the bottom of foundation
- γ=unit weight of soil
- B=width of foundation (=diameter for a circular foundation)
- $F_{cs}, F_{qs}, F_{\gamma s}$=shape factors
- $F_{cd}, F_{qd}, F_{\gamma d}$=depth factors
- $F_{ci}, F_{qi}, F_{\gamma i}$=load inclination factors
- N_c, N_q, N_γ=bearing capacity factors

Since our problem is treated as a surface footing problem and since sand is cohesionless the above equation reduces to the following:

$q_u = 1/2\gamma B N_\gamma F_{\gamma s} F_{\gamma d} F_{\gamma i}$

where $N_\gamma = .2(N_q + 1)\tan\phi)$

and $N_q = \tan^2(45 + \phi/2)e^{\Pi\tan\phi}$

therefore once $F_{\gamma s}F_{\gamma d}F_{\gamma i}$ are determined, the friction angle can be calculated.

By knowing the friction angle at which the sands fail under different size plates and loading patterns, a turfgrass system can be developed and tested using an experimental sand matching the determined friction angle from the bearing capacity equation. This sand will follow closely within the USGA specifications for gradation. The effects of angularity, gradation and particle size on the drainage of the turfgrass system will also be taken into consideration once the strength issue is solved.

Materials and Methods

Instead of selecting sands available in the market, we chose to produce six sands to be used in our study of the strength characteristics of sands. From a widely available sand (2NS) with a very wide distribution of particle sizes, experimental sand mixes were produced. A course grade, a medium grade, and a fine grade mix with a low Cu and a course grade, a medium grade, and a fine grade mix with a high Cu were developed that fit the USGA Specification. Figures 1 and 2 show the gradations for the experimental sands and their position relative to the USGA Specification envelope. On these figures the upper limit of paticle-size is indicated by the triangles and the lower limit by the diamonds. In figure 1, the three sands slope as much as the specifications allow yielding as high as coefficient of uniformity (C_u) as possible. Figure 2 shows the three sands with a relatively low coefficient of uniformity. Our interpretation would be the sands with the greater C_u would display greater strength and bearing capacity through a higher friction angle.

Figure 1. Cumulative curve for the coarse grade, medium grade, and fine grade mix with as high a C_u as possible and still remain within the USGA specifications.

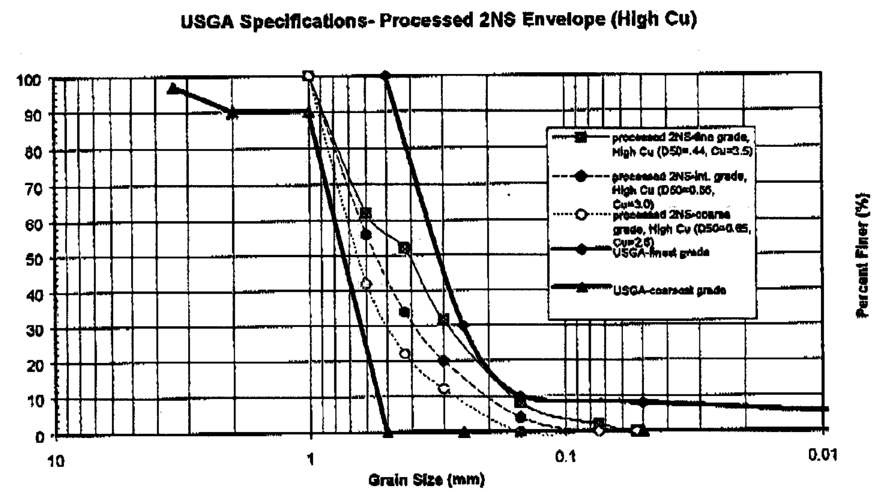
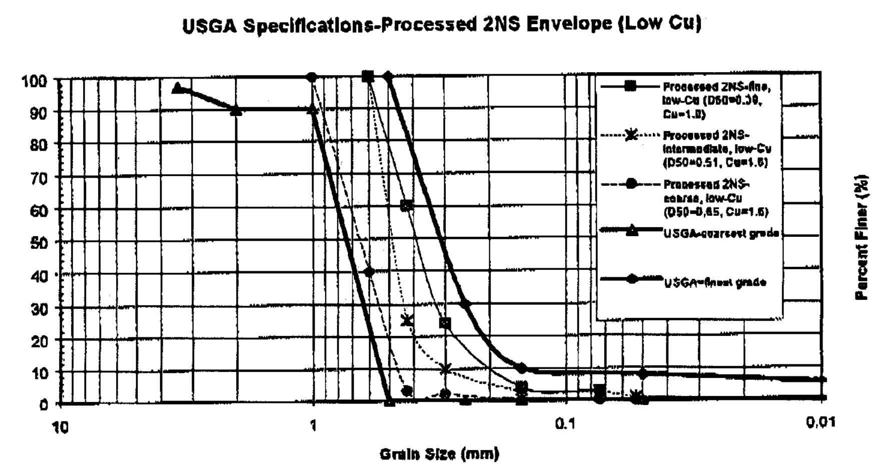


Figure 2. Cumulative curve for the coarse grade, medium grade, and fine grade mix with a low Cu.



Results and Discussion

To initiate our project we selected to study the strength of the selected sands before and after compaction under the conditions of both dry and moist. We know no putting green will be built with dry sands, but we need to understand how these sands behave with the controlling variables. From the literature review we know bulk density, porosity, moisture content, and particle-size distribution influence sand behavior.

Table 2 details soil bulk density before and after compaction under both dry and moist conditions. There are no surprises in these data as bulk density increases with compaction.

Table 2. Soil bulk density of the six processed sands dry or moist, and dense or loose.

EXPERIMENTAL DESIGN MATRIX -USGA TESTING							
Phase II - PROPERTIES OF EXPERIMENTAL SANDS							
Density (g/cm$_3$)							
COMPACTION		LOOSE		DENSE			
SATURATION		MOIST	DRY	MOIST		DRY	
SIZE-D_{50}	UNIFORMITY-C_U			initial density	density after compaction	initial density	density after compaction
COARSE	HI		1.610			1.609	1.865
	LOW		1.561			1.580	1.774
INTERMEDIATE	HI		1.642			1.614	1.897
	LOW		1.582			1.541	1.798
FINE	HI		1.579			1.621	1.871
	LOW		1.580			1.607	1.773

Table three shows the determined friction angles of the six sands when dry. We know the higher the friction angle the greater strength and bearing capacity the sand will exhibit. We have not been able to complete all tests, but our initial results indicate an increase in friction angle with compaction (expected) and that sands with a high coefficient of uniformity (C_u) have greater angles than those with lower angles (also expected).

These relationships are shown in figures three and four. In figure three you can see how the friction angle is determined by plotting the relationship of normal stress (confining force) verses shear stress (pulling force) and the angle of the resultant regression line yields the friction angle. The higher this angle the more energy is required to shear the soil and the higher the bearing capacity.

Figure four displays the changes in this relationship with sample characteristics. The greatest friction angle is derived from the well-graded sand after compaction and the lowest angle is derived from the uncompacted uniform sample. From the review of the literature, this is the expected result. Then to increase the strength and stability of high sand putting green rootzones all that is needed is to increase particle-size distribution resulting in a higher uniformity coefficient (C_u).

There are some agronomic disadvantages of increasing the Cu of sands. Figure five indicates what happens to soil porosity after compaction of the six selected sands. It is a complex relationship, but basically we find a greater reduction in porosity after compaction with the well-graded sands as compared to the uniform sands. Although we have not yet measured the hydraulic conductivity of these sands, the implication is the well-graded sands would yield a lower conductivity than the uniform sands.

Table 3. Friction angle determined from shear testing of the six selected sands when dry.

EXPERIMENTAL DESIGN MATRIX -USGA TESTING					
Phase II - PROPERTIES OF EXPERIMENTAL SANDS					
Phi angle, forced through orgin					
COMPACTION		LOOSE		DENSE	
SATURATION		MOIST	DRY	MOIST	DRY
SIZE-D_{50}	UNIFORMITY-C_U				
COARSE	HI		32.8		36.6
	LOW		29.9		39.2
INTERMEDIATE	HI		32.4		36.1
	LOW		29.2		35.5
FINE	HI		30.5		32.0
	LOW		29.8		33.6

Figure 3. Plot of shear stress verses normal stress for the intermediate sized sand with a high coefficient of uniformity (Cu).

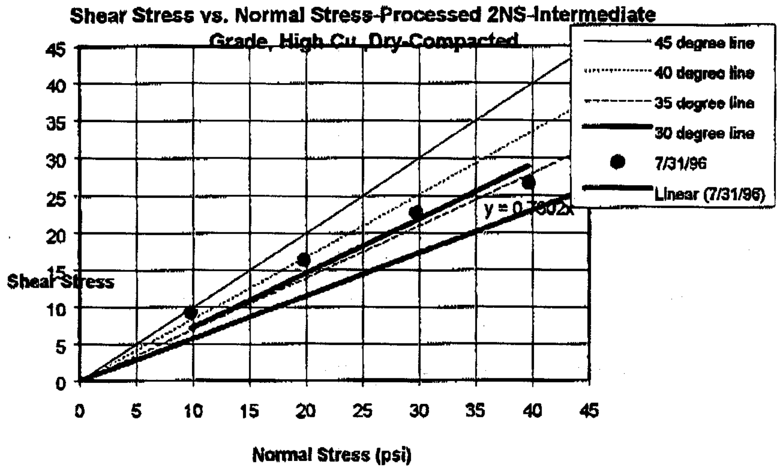


Figure 4. Plot of shear stress verses normal stress for the intermediate sized well-graded (high Cu)and uniform sands (low Cu) before and after compaction.

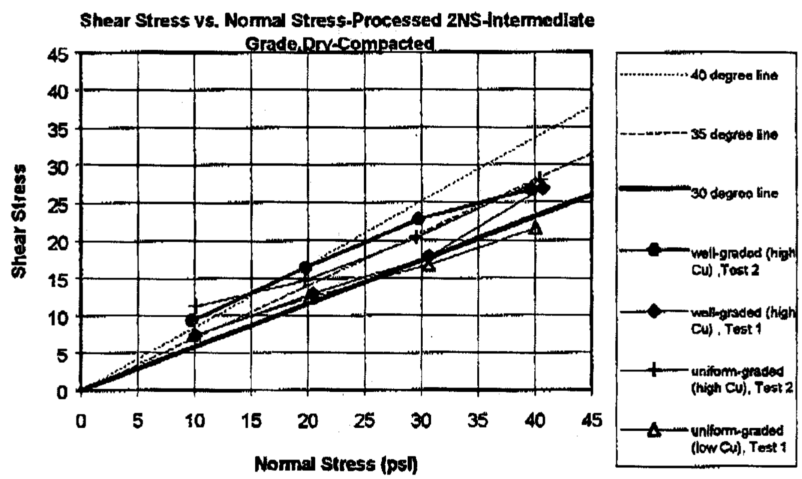
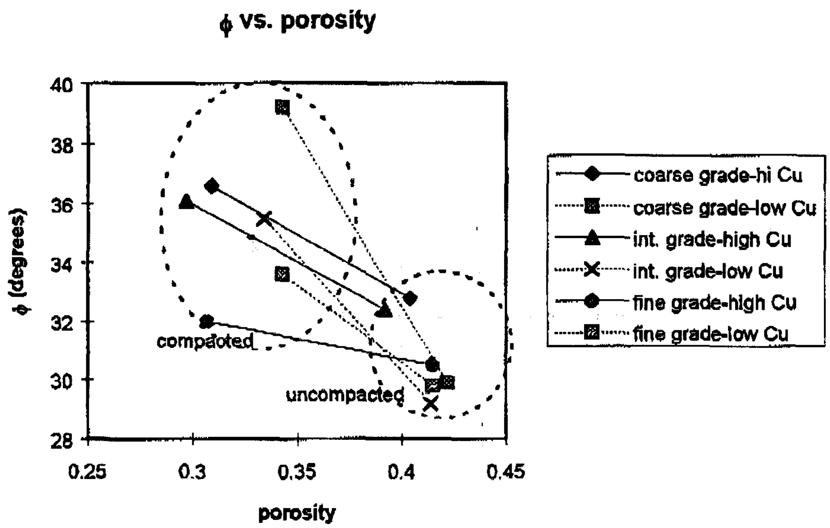


Figure 5. Plot of porosity verses friction angle before and after compaction of the six selected sands.



Summary

We feel we are making substantial progress in understanding the variables that control the engineering properties of high sand content rootzones. We know the wider the particle-size distribution of the sand, the greater will be its friction angle and the greater will be its strength and bearing capacity. Agronomically, as the distribution of the sand is widened soil porosity decreases. With a decreased porosity, saturated hydraulic conductivity will also decrease.

What we will concentrate our efforts on over the next year will be completing the testing matrix of the six selected sands, determining agronomicly important effects, and expanding our testing to the field with the CBR testing device to better understand the conditions in the field.

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Phase Two: Maintenance of Golf Putting Greens

Objectives.

The specific objectives of phase two of the proposed research have been:

1. Evaluate **three putting greens constructed** by different methods and their response to **sand topdressing** and season long **rolling** (split plot) under simulated trafficked conditions 3 to 7 years after establishment.

2. Evaluate the effects of **nitrogen and potassium** fertility on trafficked creeping bentgrass quality and wear tolerance on three putting green construction methods with a **rolling** variable.

3. Determine the long term effects of **plant growth regulators** on putting green speed and creeping bentgrass quality on three putting green construction methods with a **rolling** variable.

4. Compare **topdressing with crumb rubber from used tires to sands in putting green collars** of three putting green construction methods.

The research answering this set of objectives is being conducted at the Hancock Turfgrass Research Center on the campus of Michigan State University, East Lansing, Michigan on a 14,400 ft^2 (120 x 120 ft) experimental putting green constructed in summer 1992 and seeded in spring 1993. There are three rootzone mixes: an 80:20 (sand:peat) mixture built to USGA recommendations (Table 1); a 80:10:10 (sand:soil:peat) mixture built with subsurface tile drainage; and an unamended sandy clay loam textured (58% sand, 20.5% silt, and 21.5% clay) "push-up" style green. These putting greens are 1600 ft^2 (40x 40 ft), replicated three times, and have individual irrigation control

Table 1. Size separates for experimental green mixes at the Hancock Turfgrass Research Center.

Size separates	USGA 80:20 mix	80:10:10 mix	sandy clay loam
Gravel (> 2mm)	0.2	1.9	--
V. coarse (2.0-1.0mm)	4.8	6.8	--
Coarse (1.0-0.5mm)	34.6	31.1	--
Medium (0.5-0.25 mm)	46.7	40.4	--
Fine (0.25-0.10 mm)	12.2	16.6	--
V. fine (0.10-0.05 mm)	0.9	1.9	--
Total sand	99.4	98.7	58
silt + clay	0.6	1.3	42
% N (initial)	0.06	0.07	0.10
% Organic matter (init)	9.4	6.2	2.4

General Maintenance procedures

The area was mown six times a week at a cutting height of 0.157 inch. Topdressing of the entire area with sand was done on a light frequent basis throughout the growing season to simulate the practice by superintendents. Irrigation on each of the 9 subplots was done as necessary to prevent moisture stress. Core cultivation was performed in the fall of 1996 with a vertically operating hollow tine unit and the cores were removed.

Traffic simulator -Traffic to simulate typical wear on putting greens was applied to the plots 6 times/week with a triplex greensmower modified with spiked rollers in lieu of reel units. The rollers are 60 cm long and 20 cm in diameter. 6 mm spikes will be spaced at 2.5 cm intervals on the unit

Results and Discussion

Table 1 shows the average gain in green speed that light weight green rolling produced over non-rolled greens. Data was collected with a stimp meter on the average of three hours after rolling in 1996. Most data in Table 1 is consistent with findings from other light weight green rolling studies. The most significant finding regarding green speed was obtained from the roll then mow data. From talking with golf course managers and our students who return from internships we have learned it is often the case that greens are rolled than mowed. This most likely occurs because superintendents send out the rollers and the mowers at the same time. From this scenario we observe a substantial decrease in the potential green speed gain that mowing then rolling produce.

Table 1.
Season Averages: Net Gains from Light Weight Green Rolling in Inches

Year	1995	1996
Day Rolled	12.03	11.55
30+ Hours	5.5	7.25
50+ Hours	3.5	4.4
Rolled than Mowed	7.32	6.48

Color and quality ratings of the putting greens appear in Tables 2 and 3 respectively. Though not always statistically significant, rolling appears to have decreased color and quality. Though the data is not reported here, it is noteworthy that the 80:10:10 mix suffered a large decrease in color and quality after 14 weeks of rolling. It is our assumption the decrease can be overcome with other practices the superintendent has available.

Table 2.
Color Ratings 1996

	June 12	July 4	August 16	September 6
Rolled 3x/week	7.1	7.0	6.8	6.7
Not Rolled	7.6	6.7	7.1	7.3
Probability @ .05	.0529	.0924	.0324	.0096

Table 3.
Quality Ratings 1996

	June 12	July 4	August 16	September 6
Rolled 3x/week	6.2	6.4	6.7	6.7
Not Rolled	6.3	6.3	6.9	7.0
Probability @ .05	n.s.	n.s.	n.s.	n.s.

Dollar spot data was collected in 1995 and 1996. In 1995, Table 4, we observe the difference in dollar spot activity between rolled and unrolled plots increases as the year progresses. In 1996, Table 5, dollar spot activity was statistically significant on most dates with the rolled plots showing dollar spot reductions in the range of 2.3 to 3.5 less severity.

Table 4.
Dollar Spot Counts 1995

	June 7	July 27	August 15	September 1
Rolled 3x/week	22	226	50	201
Not Rolled	23	254	83	363

Table 5.
Dollar Spot Counts 1996

	June 14	June 24	August 2	August 7
Rolled 3x/week	8	35	9	53
Not Rolled	20	79	27	188
Probability @ .05	.0083	.0328	.0907	.0178

In Table 6, soil physical properties from samples collected on July 11, 1996 are reported. Data includes bulk density, total porosity and porosities at .04-,.1-, and .33 bar. Note that no statistically significant differences occur between rolled and non-rolled plots regarding bulk density, and total porosity. However, at .04 bar the rolled USGA and 80:10:10 greens have statistically significant less macropores than their non-rolled counterparts. The 80:10:10 mix also has less porosity at .1- and .33 bars. The data allows us to hypothesize that light weight greens rolling decreases macro-porosity without decreasing total porosity. This could explain why less localized dry spot has been observed on the rolled plots. Also of interest is more nitrogen was found in the clippings from the rolled plots. This could also be linked to the decrease in macropores and the surface observations of less dollar spot and increased pink snow mold activity on the rolled plots. Certainly more data is necessary for any conclusion to be made. On October 5, 1996 a second set of soil cores were taken for similar analysis to be performed in 1996 and 1997.

Table 6
Soil Physical Properties July 11, 1996

	Bulk Density	.04 bar	.1 bar	.33 bar	Total Porosity
USGA Rolled	1.57	20.7 b	24.7 a	26.0 a	40.7
USGA Check	1.54	23.0 a	27.0 a	28.0 a	41.0
80:10:10 Rolled	1.62	11.0 d	14.7 c	17.3 c	38.0
80:10:10 Check	1.57	14.3 c	19.0 b	21.7 b	38.3
Native Rolled	1.72	6.7 e	8.7 d	10.7 d	36.3
Native Check	1.71	5.3 e	7.0 d	8.3 d	36.3
probability @ .05	n.s.	.0288	.0270	.0133	n.s.
LSD		2.307	2.825	2.664	

Note that additional data has been collected regarding green speed, color and quality ratings, diseases incidence, clipping weights, tissue analysis, localized dry spot percentage and severity, root weights, and soil test results.

Objective 2: Soil Fertility.

On August 7, 1996 the fertility portion of the study was initiated. The fertility program is a 2 x 3 factorial design with two levels of nitrogen and three levels of potassium. This design results in six 3 foot x 17 foot plots on each of the 18 greens utilized in the light weight green rolling experiment. Methylene urea, Nutralene, was the nitrogen carrier of choice in August and September . In November of 1996, urea was the fertilizer of choice because of the quick growth response it produces in the spring. Sulfate of potash has been the only potassium carrier on the site. It has been chosen for its low burn potential and because of the roll sulfur plays in feeding black layer. Soil samples, color and quality rating data were obtained from this portion of the study in 1996. No data has been analyzed to date.

Objective 3: Plant Growth Regulators.

The study was initiated on 14 June 1996 with the first application of plant growth regulators (PGRs). The experimental design was 3 x 2 x 3 split split randomized block design. Three soil types consisted of the main plots with a rolling factor split over the construction types. A plant growth regulator factor was split over the rolling factors.

The PGR's used were trinexapac-ethyl and flurprimidol and were applied at a rate of 0.05 oz. a.i./M at five week intervals starting on 14 June 1996. The last application was on 31 August 1996. There was also a check plot. Rolling was applied three times a week. Traffic was applied with a triplex unit fitted with golf shoe spike mounted rollers six days per week to represent 150 rounds of golf per day.

Data collected included stimpmeter readings taken three times per week on the same day that rolling was applied. Both turfgrass quality and color ratings were taken on a monthly basis (scale 1-9 for each). Turfgrass rooting length was recorded on 7 August 1996. Thatch accumulation data was collected in September.

The data were analyzed using ANOVA procedures. The least significant difference test was used to analyze differences between different factors.

Results

Stimpmeter readings representing data collected during the season are presented in Table 7. There were no significant differences among soil types for stimpmeter readings until after the last PGR application which coincided with the beginning of fall in Michigan. After 31 August, the USGA construction method plots produced higher stimpmeter readings. Rolled plots produced consistently higher green speeds throughout the season. Approximately two weeks after each application there was a rolling x PGR interaction. At this point the greatest putting green speeds were achieved with a combination of PGR and rolling. These effects appeared to cease approximately 21 days after application.

Rolled plots resulted in lower color and quality during July and September ratings. The highest color and quality ratings were seen on the trinexapac-ethyl plots. Significantly longer root lengths were seen in the plots receiving no rolling verses rolled plots.

We plan to continue this study in 1997 with PGR applications starting in May and concluding in September. Stimpmeter readings will be taken three times per week, consistent with 1996 readings. The long term effects of plant growth regulators will continue to be the main objective, and comparison to the 1996 data will be initiated.

Objective 4: Crumb-rubber topdressing of putting green collars.

The study began on 23 May 1996 with the first application of crumb rubber. The experimental design was a 3 x 2 x 4 split split randomized block design. The three construction methods and rolling variables remained consistent with studies described above. The topdressing variable was split across the rolling variable.

The topdressing treatments consisted of 1/8" rubber, 3/8" rubber, 1/8" rubber and 1/8" sand mixed, and sand topdressing alone. In the interest of reducing initial shock to the turfgrass plant from excessive rubber on the surface the rubber was applied at 1/16" increments every week. The final rate of 3/8" rubber was achieved on 24 June 1996 six weeks after the initial application.

Data collected included clegg impact absorption, shear vane, quality and color ratings, thatch accumulation, rooting length and % *Poa annua* estimates.

The data were analyzed using ANOVA procedures. The least significant difference test was used to assess differences between factors.

Results

Both clegg impact absorption and shear vane readings showed an interaction between rolling and construction methods. 80:10:10 plots showed no difference in impact absorption between rolled and not rolled plots while the USGA and sandy clay loam plots produced significantly higher values in the rolled versus not rolled plots. An interaction was shown between construction methods and rolling in shear vane readings aswell. The shear vane readings produced unexpected results from the 80:10:10 as well. While the shear strength increased from rolled to not rolled plots in the USGA and sandy clay loam construction method plots, the 80:10:10 decreased in shear strength in the not rolled plots.

Percent *Poa annua* estimates resulted in an interaction between construction methods and topdressing treatments as shown in Table 8. Also, 3/8" plots had significantly lower % *Poa annua* estimates in USGA plots than the 80:10:10 and sandy clay loam construction methods.

It has been shown that the effects of crumb rubber are not seen until several months after treatment (Vanini, 1995). Crumb rubber is also known to perform to the benefit of the turfgrass stand than check plots when environmental stress is at higher levels. The summer of 1996 was cool and moist and was thus at optimum growing conditions. The long term effects of these plots will continue to be evaluated in 1997.

Table 7. Effects of construction type, rolling, and plant growth regulator treatments on stimpmeter readings, turfgrass quality and color ratings and rooting length on putting greens at the Hancock Turfgrass Research Center, 1996.

	Stimp Readings					root length	quality		color	
	6/25/92	7/18/92	7/25/92	8/8/92	9/10/92	8/7/92	7/29/96	9/10/96	7/29/96	9/10/96
Construction Type										
USGA	9.4	9.7	11.0	10.3	10.5	195.7	6.7	6.6	6.7	7.0
80:10:10	9.2	9.4	11.0	9.9	10.4	151.5	7.0	7.0	6.9	7.1
Sandy Clay Loam	9.3	9.7	11.2	9.9	10.3	200.1	7.1	7.1	7.1	7.1
LSD (0.05)	ns	ns	ns	0.4	ns	ns	ns	ns	ns	ns
Rolling Variable										
rolled	9.8	9.8	11.4	10.7	10.8	170.3	6.8	6.9	6.6	7.0
not rolled	8.8	9.5	10.7	9.3	10.1	194.6	7.1	6.9	7.2	7.1
Significance†	*	*	*	*	*	*	*	ns	*	ns
Rolling x Construction Type										
usga/rolled	10.0	9.7	11.5	10.8	11.0	186.0	6.6	7.1	6.4	7.2
usga/not rolled	8.8	9.7	10.5	9.8	10.0	205.4	6.8	6.2	7.0	6.9
80:10:10/rolled	9.8	9.7	11.5	10.7	10.7	140.6	6.8	6.8	6.5	6.9
80:10:10/not rolled	8.6	9.1	10.5	9.1	10.2	162.4	7.2	7.2	7.4	7.3
Sandy Clay Loam/rolled	9.7	9.9	11.3	10.7	10.6	184.3	7.1	6.9	7.0	6.9
Sandy Clay Loam/not rolled	9.0	9.6	11.2	9.1	10.1	215.9	7.2	7.2	7.1	7.2
LSD (0.05)	0.3	ns	0.6	0.5	ns	ns	ns	0.5	0.1	ns
Plant Growth Regulator										
Trinexapac-ethyl	9.4	9.7	11.0	10.0	10.4	176.4	7.1	7.3	7.2	7.7
Flurprimidol	9.3	9.6	11.2	9.9	10.6	190.7	6.6	6.6	6.2	6.5
check	9.2	9.6	11.0	10.1	10.3	180.2	7.4	6.8	7.3	7.0
LSD (0.05)	ns	ns	ns	ns	ns	ns	0.3	0.4	0.1	0.4
Rolling x PGR										
rolled/	10.1	9.9	11.6	10.7	10.9	159.4	6.9	7.3	6.9	7.6
rolled/cutless	9.8	9.6	11.4	10.7	11.0	181.3	6.5	6.7	5.9	6.4
rolled/check	9.5	9.9	11.2	10.7	10.4	170.1	7.0	6.8	7.1	7.0
not rolled/ Trinexapac-ethyl	8.7	9.5	10.4	9.4	10.0	193.3	7.2	7.3	7.6	7.8
not rolled/Flurprimidol	8.8	9.6	11.0	9.1	10.2	200.1	6.8	6.5	6.4	6.6
not rolled/check	8.8	9.4	10.8	9.5	10.2	190.3	7.3	6.8	7.5	7.0
LSD (0.05)	0.3	ns	ns	ns	0.4	ns	ns	ns	ns	ns

† * indicates a significant difference at the 0.05 level
NS = not significant.

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Table 8. Effects of construction type, rolling, and topdressing amendments on clegg impact absorption, shear vane, quality and color ratings and % *Poa annua* estimates on putting greens at the Hancock Turfgrass Research Center, 1996.

	Clegg	Shear Vane	—Color—		—Quality—		% *Poa annua*
	7/24/96	8/12/96	7/18/96	10/16/96	7/18/96	10/16/96	10/5/96
Construction Type							
USGA	66.6	11.2	6.7	7.1	6.7	6.8	9.7
80:10:10	64.1	12.0	6.6	7.2	6.6	7.0	17.5
Sandy Clay Loam	73.5	12.6	6.7	7.0	6.9	7.1	16.3
LSD (0.05)	ns	ns	ns	ns	ns	ns	ns
Rolling Variable							
rolled	72.2	11.4	6.5	6.9	6.4	6.5	20.8
not rolled	63.9	12.5	6.9	7.3	7.0	7.4	8.1
Significance†	*	*	*	*	*	*	*
Rolling x Construction Type							
usga/rolled	70.5	10.3	6.7	7.0	6.2	6.3	15.4
usga/not rolled	62.6	12.1	6.8	7.2	7.2	7.4	4.0
80:10:10/rolled	64.2	12.7	6.4	6.5	6.4	6.5	24.6
80:10:10/not rolled	64.6	11.3	6.9	7.9	6.8	7.4	10.4
Sandy Clay Loam/rolled	82	11.3	6.4	7.1	6.7	6.7	22.5
Sandy Clay Loam/not rolled	65.0	13.9	7	6.8	7.1	7.5	10.0
LSD (0.05)	6.2	1.2	ns	0.7	0.4	ns	ns
Topdressing Amendments							
1/8" rubber	68.6	12.1	6.8	7.1	6.8	6.9	14.4
3/8" rubber	68.9	12.1	6.6	6.9	6.6	6.9	17.4
1/8"rubber & 1/8"sand	67.7	11.3	6.6	7.1	6.6	7.1	12.9
sand	67.0	12.2	6.7	7.3	6.8	7.0	13.2
LSD (0.05)	ns	ns	ns	ns	ns	ns	ns

† * indicates a significant difference at the 0.05 level
ns = not significant

Table 9. Construction method by soil type interaction on % *Poa annua* in putting green collars, 5 October, 1996

	USGA	80:10:10	Sandy Clay Loam
1/8" rubber	11.7	20	11.7
3/8" rubber	8.7	23.5	20
sand and rubber	7.8	13.5	17.5
sand	10.7	13	15.8

LSD(0.10) = 10.4